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Analysis of inhomogeneous barrier and capacitance parameters for Al/rubrene/*n*-GaAs (100) Schottky diodes

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ABSTRACT

In this paper, 5,6,11,12-tetraphenylnaphthacene (rubrene) was prepared on *n* type GaAs (100) substrate by spin coating. The device parameters of Al/rubrene/*n*-GaAs (100) Schottky diode have been investigated by means of current–voltage (*I–V*) characteristics in the temperature range 100–300 K by steps of 50 K and capacitance–voltage (*C–V*) and conductance–voltage (*G–V*) characteristics at 1 MHz and 300 K. It was observed that ideality factors increased and barrier heights decreased with the decreasing temperature. The observed anomaly of temperature dependence of Schottky barrier height and ideality factor are explained by Gaussian distribution of Schottky barrier height in the same temperature ranges. Al/rubrene/*n*-GaAs Schottky barrier diode has been shown to have a Gaussian distribution with mean barrier height ($\overline{\Phi}_B$) of 1.076 eV and standard deviation (σ_s) of 0.119 V. Schottky barrier height (Φ_B), series resistance (R_s), and the density of interface trap states (N_{ss}) of the diode were calculated as 1.004 eV, 1.18 k Ω and 2.145×10^{11} eV^{-1} cm^{-2} for 1 MHz, respectively.

1. Introduction

Gallium arsenide (GaAs) is one of the most studied alloy semiconductor that has intrinsic electrical properties, such as higher electron mobility, direct energy gap, lower power dissipation, and high breakdown voltage [1–4]. GaAs is used in the field-effect transistors (FET), high-speed devices, laser diodes, solar cells, infrared light-emmitting diodes, and microwave frequency integrated circuits [5–11]. Organic semiconductors such as pentacene [12], anthracene [13], rubrene [14], and perylene monoimide [15] have become a very promising candidate for device applications such as field effect transistors [16], solar cells [17], and light emitting diodes [18]. Recently, much interest has been focused on organic/inorganic semiconductor contact such as perylene monoimide/*n*-GaAs [19], rhodamine 101/*n*-GaAs [20], pyronine-B/*n*-InP [21], methyl red/*p*-Si [22], TIPS-pentance/*p*-Si [23], and methylene/*p*-Si [24].

The diode parameters of Schottky diodes prepared on different semiconductor substrates are mainly found to depend on the effect of temperature in literature [15,19–21]. It was observed that the current–voltage (*I–V*) measurements deviate from the ideal thermionic emission (TE) mechanism, that is, an increase in the ideality factor (n) and a decrease of barrier height (Φ_B) with the decreasing temperature. Vural et al. [20] studied the current–voltage (*I–V*) characteristics of Al/rhodamine-101/*n*-GaAs structure in the temperature range of 80–350 K. They reported that the calculated values of n and Φ_B for Al/rhodamine-101/*n*-GaAs diode range from 6.35 and 0.23 eV (at 80 K) to 2.48 and 0.75 eV (at 350 K), respectively. Soylu et al. [21] investigated the current–voltage (*I–V*) characteristics of Au/pyronine-B/*n*-InP diode between 160 and 400 K. They observed that the barrier heights of 0.407 eV for 160 K, 0.756 eV for 400 K and the ideality factors of 1.761 for 160 K, 1.013 for 400 K for pyronine-B/*n*-InP Schottky diode, respectively. Temperature dependence of this phenomenon has also been explained by a Gaussian distribution of barrier heights due to inhomogeneous barrier heights at the organic/inorganic semiconductor interface [15,20,21]. The barrier height inhomogeneities were considered by a Gaussian distribution of the barrier heights for the rhodamine-101/*n*-GaAs and pyronine-B/*n*-InP diode by Vural et al. [20] and Soylu et al. [21], respectively. The zero-bias mean barrier height ($\overline{\Phi}_{B0}$) and the standard deviation of the barrier height (σ) values were determined as 0.93 eV and 0.112 V for the rhodamine-101/*n*-GaAs diode [20] and 0.961 eV and 0.126 V for pyronine-B/*n*-InP diode [21].

The values of capacitance and conductance of organic/inorganic semiconductor contacts depend on different parameters such as density of interface states, series resistance, interfacial layer formation, and the thickness [26–29]. Furthermore, the effect of

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interface state density (N_{ss}) can be eliminated when the capacitance–voltage (C–V) and conductance–voltage (G–V) plots are investigated at higher frequency ($f \geq 1$ MHz), since the localized charges at the interface states cannot follow an ac signal in this frequency range [26–30]. In this case, the N_{ss} are in equilibrium with the semiconductor [26–30]. Several efforts have attempted to analyze the series resistance (R_s) and interface state density (N_{ss}) of organic/inorganic semiconductor contacts by means of capacitance–voltage (C–V) and conductance–voltage (G–V) measurements in the recent years [14,26–29]. For example, Tecimer et al. [29] analyzed the admittance measurements of the Al/PTCDA/p-Si diodes and determined the values of R_s and N_{ss} depending on voltage and frequency. Tuğluoğlu et al. [26] measured the C–V and G–V characteristics of Au/perylene monoimide/n-Si Schottky diode under different frequencies and found N_{ss} to be $1.75 \times 10^{11}\,\mathrm{eV^{-1}\,cm^{-2}}$ and R_s to be 51.6 Ω of the diode at 1 MHz.

Rubrene ($C_{42}H_{28}$, 5,6,11,12-tetraphenylnaphthacene) among organic semiconductors is one of the most promising semiconductors owing to its high electrical conductivity and mobility for technological applications such as organic light emitting diodes (OLEDs) [31], organic photovoltaic (OPV) devices [32], thin film transistors (TFTs) [33], field effect transistors (FETs) [34], and so on. There are a number of experimental works on the effect of organic semiconductor material in device applications. However, we still do not know the temperature dependent I–V characteristics of Al/rubrene/n-GaAs structure. Therefore, electrical characteristics need to be studied in detail. In literature, very little experimental information is still available on the barrier formation at organic/inorganic semiconductor interfaces and the temperature dependent conduction mechanisms of the interfaces at a wide temperature range.

The goal of this work is to investigate potential use of rubrene material for GaAs based electronic devices and determine the electrical properties of Al/rubrene/n-GaAs diode by means of I–V measurements in the temperature range from 100 to 300 K and C–G–V measurements at room temperature (300 K). The temperature dependence of the ideality factor and the barrier height is discussed using thermionic emission theory with a Gaussian distribution of the barrier heights around a mean value due to barrier height inhomogeneities prevailing at the metal-semiconductor interface. Furthermore, the series resistance and interface state densiy properties of the diode are determined by means of admittance method and Hill–Coleman method, respectively.

2. Experimental procedure

The n-type GaAs (100) substrate used in this study has a 500 μm thickness and 20 Ω cm resistivity. Initally, the substrate has been cleaned in methanol and acetone using ultrasonic agitation for 3 min and rinsed in de-ionized water (18 M). Firstly, The GaAs substrate is cleaned using the Radio Corporation of America (RCA) cleaning method [19]. Ohmic contact with low resistance is made by evaporation of indium (In, 99.99%) metal with thickness of 150 nm in 5×10^{-6} Torr on the backside of the GaAs substrate and then by thermal annealing at 400 °C for 2 min in vacuum. The rubrene was dissolved in toluene with a concentration of 10 mg ml^{-1} Ω. This solution was stirred for 5 min at a magnetic stirrer. The solution was prepared and kept in MBraun glovebox maintaining a nitrogen inert atmosphere. A rubrene organic film is prepared on the GaAs substrate by the spin coating technique at a spinning rate of 1200 rpm for 60 s with a Laurell Spin Coater. Schottky contacts are prepared on rubrene organic film with a diameter of 2 mm by a metal shadow mask by evaporating aluminum (Al, 99.999%) metal with thickness of 150 nm in 5×10^{-6} Torr. High purity indium and aluminum metal contacts were thermally evaporated from a tungsten filament in a high vacuum coating unit (Edwards, E-306A) to form the bottom and top contact onto rubrene/n-GaAs film surface, respectively. The rubrene layer thickness is determined as 116.1 nm from measurement of the interfacial layer capacitance in the accumulation region. The current–voltage (I–V) measurements were performed by a Keithley 2410 SourceMeter at temperature range from 100 to 300 K using an ARS Closed Cycle Cryostat Model DE202 AI and a Lake Shore model 331 temperature controller. Capacitance–voltage (C–V), conductance–voltage (G–V) characteristics were carried out with an HP 4192A LF (5 Hz–13 MHz) Impedance Analyzer at 1 MHz.

3. Results and discussion

3.1. Current–voltage characteristics of the diode

According to the thermionic emission theory, a Schottky diode for $V > 3kT/q$, The current–voltage (I–V) curves can be investigated by the following equations [35,36]:

$$I = I_0\left[ex\,p\left(\frac{qV}{nkT}\right) - 1\right]; I_0 = AA^*T^2 exp\left(-\frac{q\Phi_B}{kT}\right) \quad (1)$$

where A is the Schottky contact area, A^* is the effective Richardson constant equals to 8.16 A/cm^2 K^2 for n-type GaAs [19],q is the electronic charge, is the saturation current, n is the ideality factor of diode, Φ_B is the barrier height, T is the absolute temperature. The Φ_B and n values of Al/rubrene/n-GaAs can be determined from intercepts and slopes of the voltage dependent of forward-bias ln I curve (inset of Fig. 1), respectively, as [35,36]:

$$\Phi_B = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_0}\right) \text{and} n = \frac{q}{kT}\left(\frac{dV}{dlnI}\right) \quad (2)$$

Fig. 1 displays the current–voltage (I–V) characteristics of the Al/rubrene/n-GaAs diode in the temperature range of 100–300 K. As seen, the forward and reverse-bias semi-logarithmic ln I–V and I–V characteristics of the Al/rubrene/n-GaAs diode show good rectifying behavior at all temperatures. The saturation current (I_0) values were determined from the linear portion intercept of log I–V at $V = 0$ in the temperature range of 100–300 K. The n and Φ_B values of the diode in the temperature range of 100–300 K are calculated

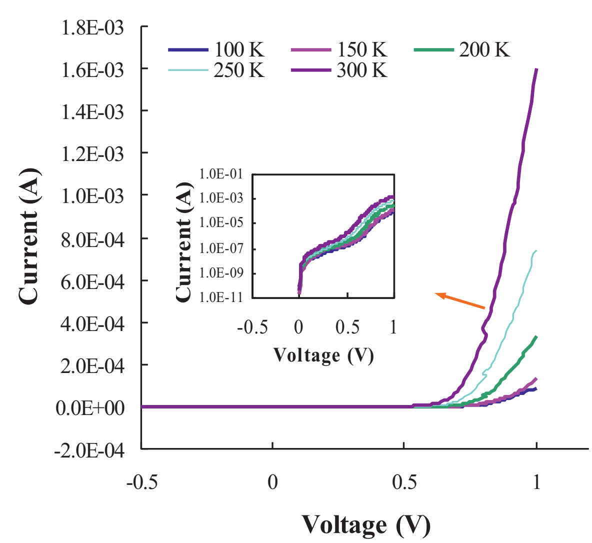

Fig. 1. Current–voltage characteristics of Al/rubrene/n-GaAs diode in the temperature range of 100–300 K.